

# ANALYSIS OF THE COOL DOWN RELATED CAVITY PERFORMANCE OF THE EUROPEAN XFEL VERTICAL ACCEPTANCE TESTS

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ABSTRACT. It has been reported in [1, 2] that the cool down dynamics across  $T_c$  has a significant influence on the observed quality factors  $Q_0$  of a cavity, which is most likely due to trapped flux [3]. In this document we show the results of the investigation if such a correlation can be observed during the European XFEL cavity production [4].

## 1. CRYOSTAT DESIGN AND COOL DOWN PROCEDURES

The cool down procedures at the AMTF vertical test stands were mainly automated (PLC-based) and only required operator supervision [5, 6]. Cernox<sup>TM</sup> temperature sensors at one of the inserts were used to commission the procedures and monitor the thermal stress on the inserts [7]. Carbon temperature sensors (TVO) [8] glued to the outside of the cryostats are used during normal operation, see Figure 1. One sensor was located at a position corresponding to a location between equators three and four of the cavity; two other sensors were 880 mm above and below this location. The configuration of the TVO sensors had a significant impact on the possibility to observe the cool down dynamics directly at the cavity. This instrumentation was designed for a well-defined operation and control of the cryogenic system and any cold vertical tests were performed in stable cryogenic conditions. During series vertical testing neither the inserts nor the individual cavities were equipped with temperature sensors.

The cool down from 300 K to 100 K took approximately 12 hours, which represents an average cool down rate of 5 mK/s. The cryostat remains at 100 K for 4-6 hours to test for hydrogen Q-Disease (see chapter 9.4 in [9]), after which the cavity is further cooled to 4 K. The cool down rate across  $T_c$  was of the order of 200 mK/s at which point a maximal longitudinal temperature gradient along the cavities of up to 25 K was observed.

## 2. DC MAGNETIC FIELD IN THE TEST CRYOSTATS

One significant influence on the  $Q_0$  (more specifically the RF surface resistance) is the ambient magnetic field during cool down. Hence a suppression of the ambient magnetic field below a value of 10-20 mG is necessary to achieve the European XFEL specifications.

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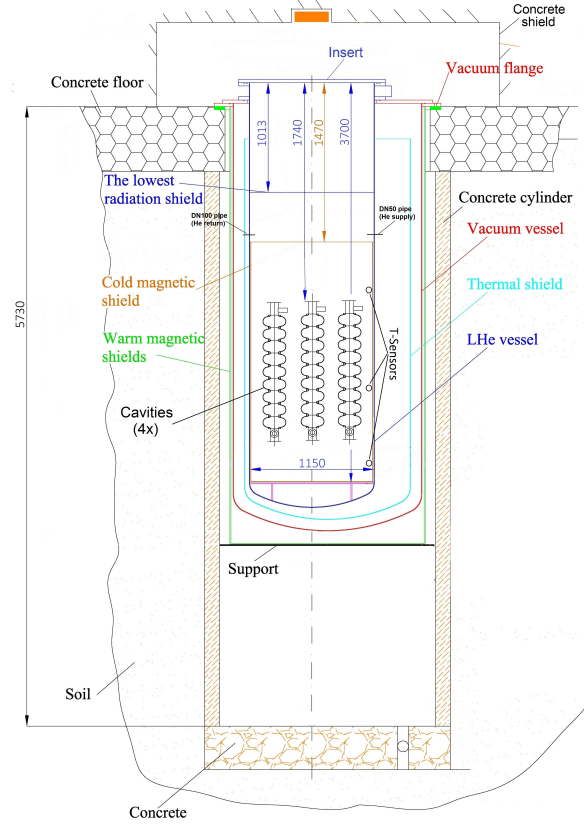


FIGURE 1. Section diagram of the vertical test cryostat. Note that only three of the four cavities are visible. The TVO sensor positions are indicated on the right side of the cryostat. One sensor is located at the vertical position corresponding at a location between equators three and four of the cavity (which will be further used in this analysis); two other sensors were 880 mm above and below this location.

The magnetic field in the concrete pit for the two vertical cryostats was approximately 400 mG. Simulations showed that two magnetic shields were necessary: a double-walled warm magnetic shield around the cryostats (300K), and an additional smaller one inside of the cryostat at 2K. All shields were cylindrical with a closed bottom (see Figure 1). Measurements of the magnetic field inside of the cryostat were made at room temperature and are given in Figure 2.

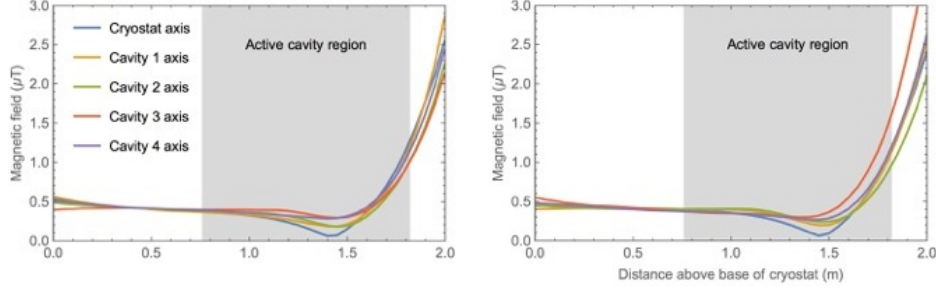


FIGURE 2. Magnetic field distribution inside the cryostats XATC1 (top) and XATC2 (bottom) of the

### 3. COMPARISON OF TVO AND CERNOX<sup>TM</sup> SENSORS

Figure 3 shows a comparison between the TVO sensor at the height of the iris between equator three and four and three Cernox<sup>TM</sup> sensors attached at the insert (1 cm below the cavity).

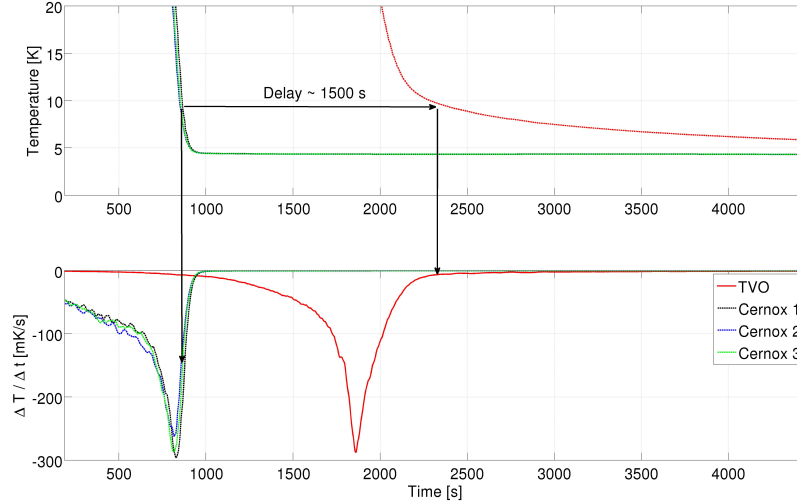


FIGURE 3. Top: Temperature curves for 3 Cernox<sup>TM</sup> and 1 TVO sensor. A delay caused by the horizontal displacement of the sensors is visible (indicated by the horizontal arrow) and the TVO sensor shows a less steep behavior across  $T_c$ . Bottom: The cool down rate of the sensors. The rate across  $T_c$  is indicated by two downward arrows. A difference of the cool down rate of two orders of magnitude was observed.

There is a delay of about 1500 s between the Cernox<sup>TM</sup> and TVO sensors, which is expected due to heat diffusion caused by the horizontal displacement of the sensors and the thermal capacity of the cryostat.

Hence, the to be compared cool down rate should not be identified by a given absolute time, but by a certain temperature achieved at the very sensor, e.g.  $T_c$ . Figure 3 (bottom) shows the time derivatives (instantaneous cool down rate) of the sensors. A much lower rate is observed in the TVO sensor at  $T_c$  than with the corresponding Cernox<sup>TM</sup> sensors. For the measurement shown in Figure 3, the cool down rate at the insert across  $T_c$  was 125 mK/s while at the TVO sensors outside the helium tank the corresponding value was 5.4 mK/s a direct consequence of the heat capacity of the helium tank. As only the TVO data was available for the production testing, an additional test to gain data using the insert fully-instrumented with Cernox<sup>TM</sup> sensors (of which Figure 3 is an example) were used to interpret the TVO data in terms of the cool down rates at the cavity. The observed difference could be understood as a consequence of the design of the test stand and sensor positions. Since this set up didn't change along the cavity production, the underlying assumption is that the observed difference of the cool down rates of the different sensors is constant for all the cool downs. Hence, although the TVO sensors underestimate the cool down rate across the cavity, this underestimation is the same for all cool downs.

#### 4. COOL DOWN RATE AND QUALITY FACTORS OF THE EUROPEAN XFEL CAVITIES

Since up to four cavities can be installed in one insert, groups of cavities tested together will have the same cool down rate. Cool down data was available for a total number 168 (199) cool downs for test stand V1 (test stand V2), which yielded a total of 457 (516) individual cavity tests. Figure 4 shows the temporal development of the cool down rates across  $T_c$  for the two cryostats used.

The use of cryostat V1 has to be stopped due to a blocked flange which permitted the further operation, hence no more data points are available after approx. two years. The uniform behavior at the beginning of the production (up till day 200), was to ensure mechanical stability of the inserts. The experience gained after a first operational period showed that the mechanical stress due to cool down is less than expected and a faster cool down was possible. Hence the change of the observed cool down rates.

The Figures 5 and 6 show the scatter plot of the measured  $Q_0$  at a gradient of 4 MV/m in a vertical test versus the cool down rate across  $T_c$ , grouped according to cavity location in the test stand.

The first observation is that no correlation was found. The same observation is true for  $Q_0$  at higher fields. The second observation is the double Gaussian distribution of the cool down rate for the vertical test stand V1 (Figure 5) and a large tail to higher values in the cool down rate for vertical test stand V2 (Figure 6). This corresponds to the temporal distribution of the cool down rates as shown in Figure 4.

As suggested in [3], the spatial temperature gradient during cool down may be the more precise parameter to model the influence on the cavity. Hence, a second analysis considering this parameter was performed. The spatial gradient was approximated by taking the temperature difference of the upper and lower TVO sensor of the cryostat when the lower TVO sensor measured  $T_c$  (in contrast for the cool down rate, where the middle sensor was utilized). The Figures 7 and 8 show the result of this analysis.

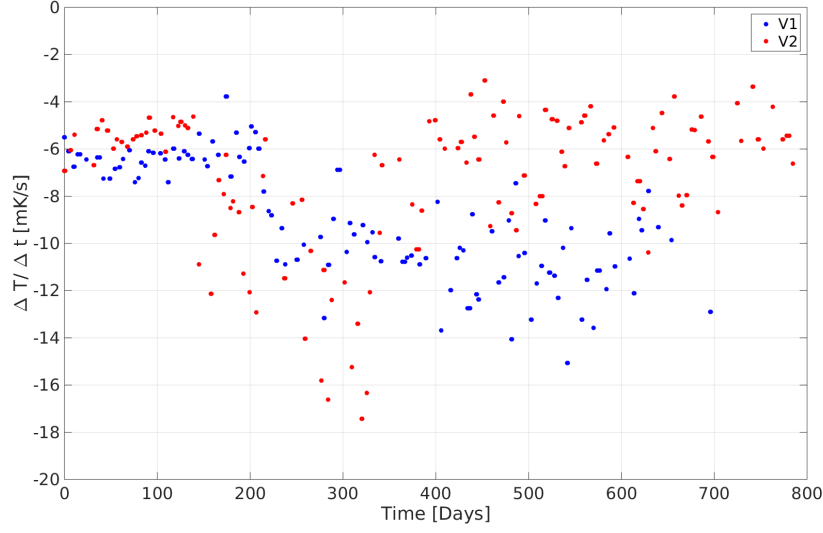


FIGURE 4. The x-axis shows the date when the cool down took place, relative to the beginning of the cavity production, while the y-axis shows the cool down rate across  $T_c$  for the respective cool down.

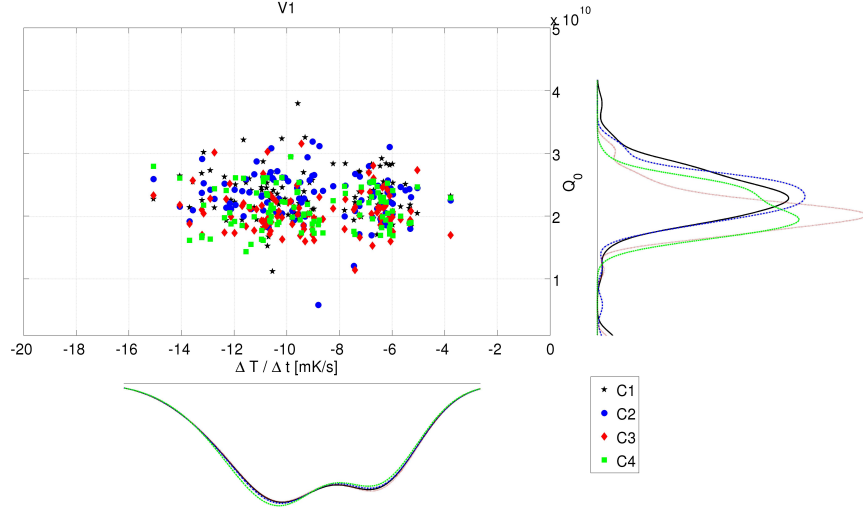


FIGURE 5. Scatterplot of the  $Q_0$  at 4 MV/m measured in a vertical test versus the estimated cool down rate, grouped by the four possible cavity positions C1-4 in vertical test stand V1. The histograms show the projected distributions.

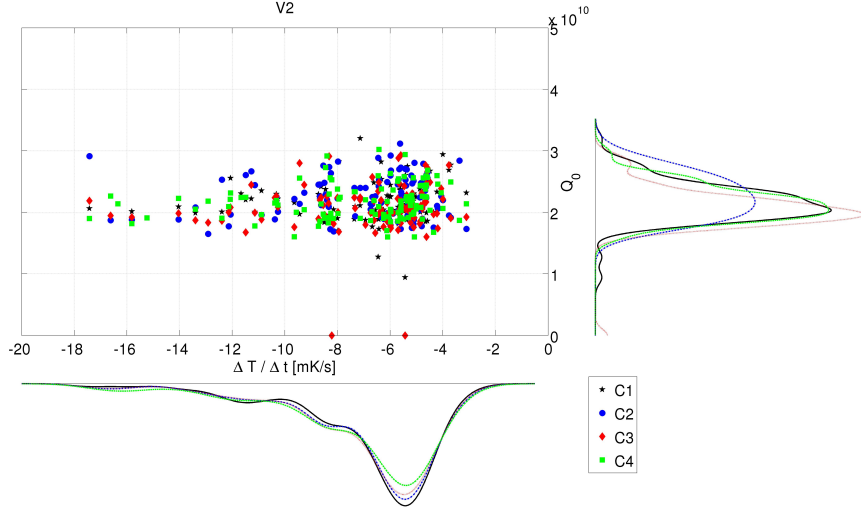


FIGURE 6. Scatterplot of the  $Q_0$  at 4 MV/m measured in a vertical test versus the estimated cool down rate, grouped by the four cavity positions in vertical test stand V2. The histograms show the projected distributions.

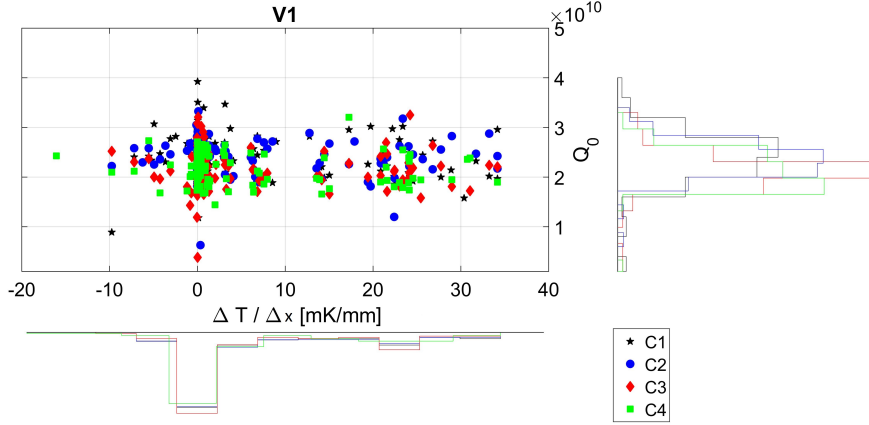


FIGURE 7. Scatterplot of the  $Q_0$  at 4 MV/m measured in a vertical test versus the approximated spatial temperature gradient, grouped by the four cavity positions in vertical test stand V1. The histograms show the projected distributions.

Again, no correlation is observed. In addition, it has to be mentioned that the negative values happened when the filling & cooling of the cryostat has been done from top to bottom. This was only done in a few cases and were caused by technical reasons. Extreme values of the spatial temperature gradient correspond to high cool down rates, which show the consistency of this analysis.

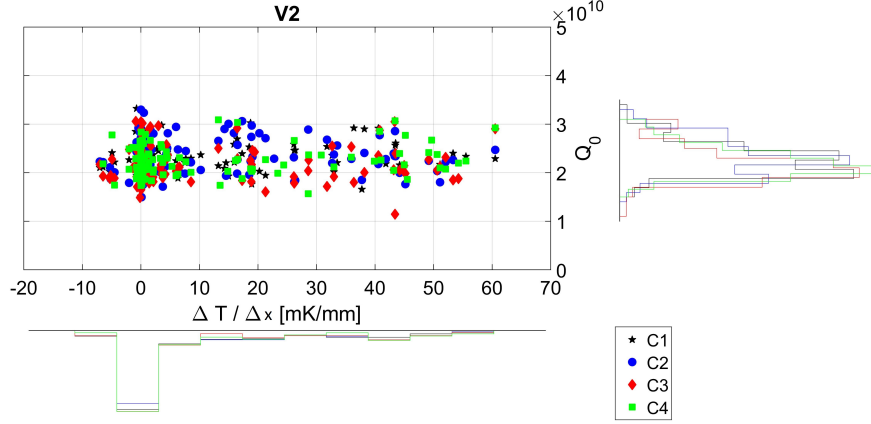


FIGURE 8. Scatterplot of the  $Q_0$  at 4 MV/m measured in a vertical test versus the approximated spatial temperature gradient, grouped by the four cavity positions in vertical test stand V2. The histograms show the projected distributions.

## 5. SUMMARY

The fact that no correlation between the cool down rate or the spatial temperature gradient and the quality factor  $Q_0$  is observed is not necessarily in contradiction to the observations made elsewhere, but is simply given by the design of the diagnostics at the test stand. The location of the temperature sensor and the strong influence of the helium cryostat described above may prevent the observation of any correlation.

It has to be noted that this diagnostic design is sufficient for the acceptance tests performed for the European XFEL cavity production, since any measurements were done after a certain latency to give the whole system time to achieve a thermal equilibrium. This process is well monitored with this diagnostic system.

## 6. ACKNOWLEDGMENTS

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